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Energy Procedia 75 (2015) 1126 – 1131

Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

Analytical Off-design Characteristics of Gas Turbine-Based CCHP System

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Abstract

Grounded on the typical analytical off-design performances of some basic CCHP (combined cooling, heating and power) components, off-design characteristics of a gas turbine-based CCHP system were analyzed and summarized. The results and discussion show that, at full power load of the gas turbine, the CCHP relative cold output Q^r_c varies from 0~1.2, and the corresponding relative heat output Q^r_h from 1~0. The CCHP system supplies 23.7% of the design cold capacity or 22.7% of the design heat capacity at empty power load. CCHP economic exergy efficiency and thermal efficiency both rise with the increase of power output, and trend towards a slight decline at a near-full cooling load of chiller. In a wide operation range of CCHP, economic exergy efficiency and thermal efficiency both rise with the increase of cooling load. Higher ambient temperature results in lower relative capacity of cold, heat and power. It is proposed that renovation technologies such as gas turbine inlet air cooling, steam injected gas turbine and HRSG supplementary firing be applied to weaken the effect of the ambient temperature on CCHP system. The quantitative results are meaningful for optimal configuration and economical operation of the energy systems.

Peer-review under responsibility of Applied Energy Innovation Institute

Keywords: CCHP, absorption chiller; off-design performance; analytical solution

1. Introduction

CCHP system is one of the keys of distributed decentralized energy resources. Due to its advantages like energy conservation, friendly environment and reliable economical electric power supply, etc, gas turbine-based CCHP is being widely concerned and fleetly developed [1-3]. Most of the CCHP systems often run under off-design situations due to the changes of the load or the ambient temperature or both.

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Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.528

The current researches on CCHP systems focus on (1) optimizing on the configuration of the CCHP components [4,5], (2) economic and energy utilization evaluation of CCHP systems [6-8], and (3) part-load performance of CCHP systems [9,10]. The former two researches are usually based on the design performance or simple part-load performance of CCHP systems. Wang et al analyzed the energy flow of CCHP system and deduced the primary energy consumption following the thermal demand of building[4]. Liu et al presented a matrix modeling approach to optimize the CCHP system and the size of the power generation unit was optimized to achieve the optimal performance of the CCHP system[5]. Heejin Cho et al presented an optimization of the operation of CCHP systems for different climate conditions based on operational cost, primary energy consumption, and carbon dioxide emissions using an optimal energy dispatch algorithm[7]. Utilizing the typical analytical solution of single shaft constant speed gas turbine and considering the variation of heat transfer coefficient of HRSG (heat recovery steam generator), the part-load performance of CCHP with gas turbine and storage system was analyzed by Feng and Jin [9].

The authors previously studied the influence of the ambient on gas turbine based CCHP system available capacity and efficiency form the viewpoint of off-design performance[3]. The objective of this paper is to investigate the part-load capacity and efficiency of a gas turbine-based CCHP system, using analytical approach of off-design performance analysis[10-14]. The understanding of CCHP off-design characteristics provides a basis for optimizing the system configuration when the demanded loads of cooling, heat and power are given.

2. System configuration and the component performance analysis method

2.1. System description

The CCHP system studied in this paper is composed of a constant speed gas turbine, a saturated steam HRSG (heat recovery steam generator) and a steam-driven double effect LiBr-water absorption chiller. The configuration is described in Fig. 1.

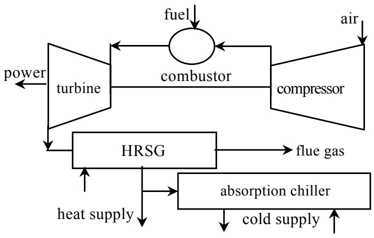

Fig. 1. Scheme of CCHP system.

The design capacity of the HRSG and the absorption chiller is selected according to the ISO (the ambient temperature $t_a = 15$℃, relative humidity $RH = 60\%$) performance of gas turbine. The design pressure ratio of gas turbine $\pi_{c0} = 6$, the temperature ratio τ_0=4.5. For the HRSG, the design steam pressure is selected as p_{s0}=0.9MPa, the design pinch point temperature difference ΔT_{p0}=16.2K, the design approaching temperature difference $\Delta T_{a0} = 18$K, the design feed-water temperature $T_{w0} = 378$K. The design parameters of the absorption chiller are listed as follows, supply chilled water temperature $t_{cs} = 7$℃, inlet cooling water temperature $t_{wi} = 32$℃, the heating steam pressure is equal to the design steam pressure of HRSG.

Under off-design situations, it is specified that the chiller cooling load rate R ranges from 15%~110%, supply chilled water temperature t_{cs} =7℃, inlet cooling water temperature t_{wi} varies from 18 to 36℃.

Approximately, the inlet cooling water temperature t_{wi} is assumed to be 4℃ lower than ambient temperature t_a.

2.2. Analytical method of the basic component performances

With the analytical method for the typical off-design performance of gas turbine [10] and saturated steam HRSG [13,14], some off-design performances of the CCHP sub-system under various partial loads at different ambient temperature can be obtained.

In Fig.1, saturated steam extraction from the evaporator of HRSG is applied. The quantitative and qualitative analysis accordantly show that, the steam production analytical solution is reliable in various off-design conditions while the steam temperature obtained by analytical solution is available for the case of near-design conditions. However, the presented regression solution for steam temperature is applicable in wide off-design conditions[14].

LiBr-water absorption chiller is often found in multifunction energy systems. The experiential part-load performance model for common chillers presented by DOE-2 is one of the analytical methods to solve chiller performances. DOE-2 model for building consumption analysis and energy efficiency evaluation applies curve regression method and presents a model for the typical off-design performance of chillers. Its validity has been tested as an approximate, general and typical model for predicting the chiller performance [12].

This paper integrates a modified DOE-2 model for LiBr absorption chiller with the analytical solution for the off-design performance of HRSG and gas turbine, to analyze the part-load performance of a gas turbine-based CCHP system.

3. Analytical performance of the CCHP system

3.1. Overall part-load capacity of CCHP

Adjusting the turbine inlet gas temperature T_3 and proportion of the steam flow for heating the chiller generator to total steam production (X_c for short and will be discussed later), the overall off-design performance of CCHP system is attained and presented in Figs. 2a~2c, where the variation range of cold, heat and power output is shown. At constant speed operation of gas turbine, there is generally a stall margin between the operation line of T_{3max} and the compressor surge. Therefore, The CCHP operation bounds are limited by turbine maximum inlet gas temperature T_{3max} and chiller load rate R. The maximum

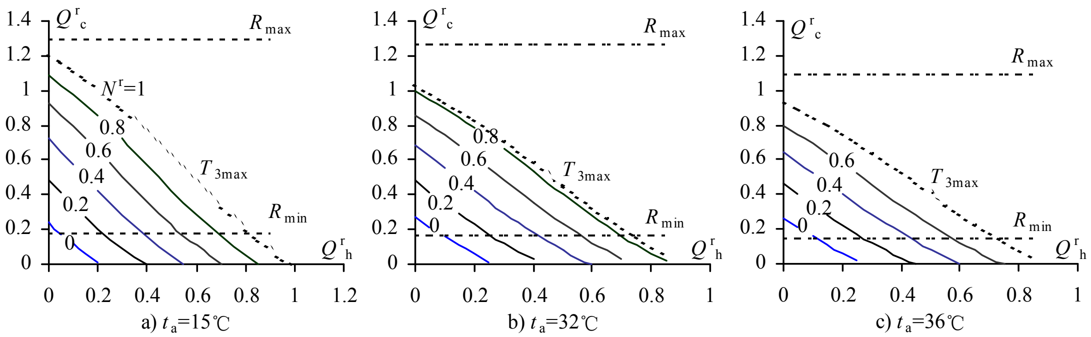

Fig. 2. Relative available capacity of the CCHP system at various power loads.

load rate of absorption chiller is set at 1.1 (or 110%) and the minimum load rate at 0.15 (or 15%). The supply chilled water temperature remains 7℃. When the condensed water of heating steam remains the constant, relative heat output $Q_h/Q_{h0}=1-X_c$.

Fig. 2a shows the overall part-load performance map of CCHP system at t_a=15℃. It can be seen that, at constant speed and full power load operation, the CCHP relative cold output Q^r_c varies from 0~1.2, and the corresponding relative heat output Q^r_h from 1~0. The CCHP system supplies 23.7% of the design cold capacity or 22.7% of the design heat capacity at empty power load.

Figs. 2b and 2c show the overall part-load performance map for CCHP at t_a=32℃ and t_a=36℃ respectively. Apparently, higher ambient temperature results in less relative capacity of cold, heat and power. For example, at t_a=36℃ (the corresponding cooling water temperature t_{wi}=32℃), relative cold output Q^r_c ranges from 0 to 0.93, the corresponding relative heat output Q^r_h from 0.85 to 0 and relative power output N^r from 0 to 0.84.

3.2. Discussion on CCHP efficiency

3.2.1. Definitions of CCHP efficiency

Generally the efficiency η of CCHP system can be expressed as

$$\eta=(N+\alpha\cdot Q_c+\beta\cdot Q_h)/(G_f\cdot Hu) \quad (1)$$

where, G_f is the fuel consumption and Hu is the low heat value of fuel. Q_c, Q_h and N represent cold, heat and power production respectively.

When α stands for the price ratio of cold to electric power, β for that of heat to electric power, the Eqs. (1) is an expression for economic exergy efficiency η_{ec}.

When $\alpha=\beta=1$, the Eqs. (1) is an expression for thermal efficiency η_{th}.

Define coefficient X_c as the proportion of the steam flow $G_{s,c}$ for heating the absorption chiller to total steam production G_s, i.e., $X_c=G_{s,c}/G_s$. In practice, X_c indicates the proportion of the cold to heat produced by CCHP or the load rate of chiller. When condensed water temperature remains a constant,

$$\eta_{ec}= Q_s\cdot[r+\alpha\cdot X_c\cdot COP_{Xc}+\beta\cdot(1-X_c)]/(G_f\cdot Hu) \quad (2)$$

where, Q_s is the heat capacity of CCHP at off-design conditions; r is the ratio of power to total heat, i.e., $r=N/Q_s$; COP is the performance coefficient of chiller and is related with t_a and X_c etc.. A coefficient γ is defined as the ratio of steam production to fuel consumption, i.e., $\gamma=G_s/G_f$. Thus relative efficiency is further expressed as,

$$\eta_{ec}/\eta_{ec0}=\frac{\gamma}{\gamma_0}\cdot\frac{r+X_c(\alpha\cdot COP_{Xc}-\beta)+\beta}{r_0+\alpha\cdot X_{c0}\cdot COP_{15,Xc0}+\beta(1-X_{c0})} \quad (3)$$

where, the subscript 0 stands for the design value, COP_{15} is the coefficient of performance of chiller at t_a=15℃（t_{wi}=18℃ accordingly）. COP_0 is chiller COP at the design condition, i.e., t_{wi}＝32℃ generally.

3.2.2. Overall part-load efficiency of CCHP

The design parameters of CCHP components are selected the same as mentioned above and other parameters of CCHP efficiency are listed as follows, r_0=0.52, COP_0=1.3, X_{c0}=0.8, $COP_{15,Xc0=0.8}$ equals 1.65. The price of cold, heat and power varies in different countries or zones, in this paper α=0.8 and β=0.3 are assumed for economic exergy efficiency.

According to Eqs. (3), relative economic exergy efficiency and relative thermal efficiency at part-load condition are worked out and shown in Figs. 3a~3c. The operation bounds are ignored and given in Figs. 2a~2c for reference. When chiller load rate $R<0.15$, the CCHP system operates in the mode of CHP (combined heat and power). For example, when $X_c=0.2$ in Fig. 3a, the CCHP operates within the range of $N^r=0.9\sim1$, since $R<0.15$ at the condition of $N^r<0.9$ and $X_c=0.2$ or $Q^r_h=0.8$ (see Fig. 2a).

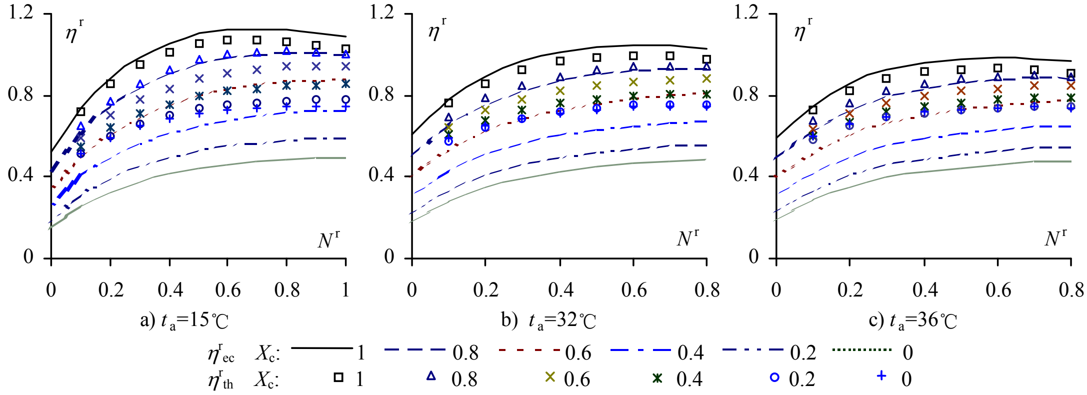

Fig. 3. Part-load CCHP efficiencies at different X_c.

Figs. 3a~3c indicate that, both the relative economic exergy efficiency and the relative thermal efficiency rise with the increase of power output within a wide operation range. However, the two relative efficiencies trend towards a decline with the increase of power output when X_c approaches 1. This is due to the decrease in chiller *COP* at a near full load and overfull load ($R>R_{opt}$).

At low power load operation, relative economic exergy efficiency and economic exergy efficiency both increase rapidly with power increase; while varies slightly at high power load. The reason is that, gas turbine efficiency, HRSG steam production and chiller *COP* all rise rapidly with the increase in power load, especially at a low power load. At a high power load, chiller *COP* trends towards a decline at the condition of high X_c.

The proportion of the chiller heating steam flow to the total steam production, i.e. X_c, has a complicated influence on CCHP efficiency. Within the wide operation range of CCHP, relative economic exergy efficiency and relative thermal exergy efficiency both rise with the increase of X_c. In general, in the case of the design parameters given in this paper, economic exergy efficiency decreases with the increase of X_c when $COP<\beta/\alpha=0.375$, the same way for thermal efficiency when $COP<1$.

4. Conclusions

The typical overall off-design characteristics of a CCHP system are obtained and studied by adjusting the turbine inlet gas temperature T_3 and proportion X_c of the steam flow for heating absorption chiller to the total steam production. CCHP efficiencies with different definitions are presented and discussed.

At full power load operation, the CCHP relative cold output Q^r_c varies from 0~1.2, and the corresponding relative heat output Q^r_h from 1~0. The CCHP system supplies 23.7% of the design cold capacity or 22.7% of the design heat capacity at empty power load.

At full power load operation, higher ambient temperature results in less output of heat and power, and lower available capacity of cold due to the increase in cooling water temperature of chiller. The efficiencies almost remain stable first and then drops with the increase of ambient temperature at a higher value of X_c ($X_c \geqslant 0.6$ approximately). At a lower value of X_c ($X_c < 0.6$ approximately), the two relative efficiencies both decrease slightly with the increase of ambient temperature.

CCHP economic exergy efficiency and thermal efficiency both rise with the increase of power output, and trend towards a slight decline when X_c approaches 1. In a wide operation range of CCHP, the two efficiencies both rise with the increase in the value of X_c.

It is proposed that renovation technologies such as gas turbine inlet air cooling, steam injected gas turbine and HRSG supplementary firing be applied to improve the adaptivity to the demanded loads.

Acknowledgments

This work was supported by Guangdong Province Key Laboratory of Efficient and Clean Energy Utilization (2013A061401005), South China University of technology.

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